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MAP DIMENSIONALITY AND FRAME OF REFERENCE FOR TERMINAL
AREA NAVIGATION DISPLAYS: WHERE DO WE GO FROM HERE?

BY

CHRISTOPHER RICHARD RATE

B.S., United States Air Force Academy, 1992

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Psychology
in the Graduate College of the
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MAP DIMENSIONALITY AND FRAME OF REFERENCE:
REVOLUTIONARY DISPLAYS FOR TERMINAL AREA NAVIGATION

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University of Illinois at Urbana-Champaign, 1993
Christopher D. Wickens, Advisor

The purpose of this study was to examine and compare a more radical design of instrument approach plates with a more traditional representation. Thirty subjects, 25 males and 5 females, were divided into two groups of fifteen for assignment to the map frame of reference condition (fixed or rotating maps). Each subject flew eight landing approaches, four with the two-dimensional display and four with the three-dimensional display. Subjects were given two primary tasks: fly the aircraft to minimize flight path deviations, and answer questions related to measures of situation awareness.

The results indicated that the two separate display panels in the two-dimensional display were superior to the three-dimensional display in regards to the dependent measures of flight control and judgment tasks. Furthermore, the rotating map supported flight control better than the fixed map while there was relatively no difference for measures of situation awareness. It is apparent that acceptance of three-dimensional displays for approach plates is dependent on further investigation in this domain.

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TABLE OF CONTENTS

INTRODUCTION

As a result of the undeniable complexity of the aviation environment, pilots are faced with multiple tasks differing in priority. While every component of aviation is important, navigation and landing approach procedures appear to present particularly challenging problems for the aviator. Two separate surveys of NASA's Aviation Safety Reporting System (ASRS) incidents depict the not uncommon occurrence of geographical disorientation, resulting in pilots landing their aircraft at wrong airports (Antunano, Mohler, & Gosbee, 1988; Williams, Tham, & Wickens, 1992). Each survey identifies that over 60% of these incidents occurred during visual meteorological conditions.

Even though geographical disorientation is a concern (Antunano & Mohler, 1988), it is primarily a contributing factor to the overall problem of approach and landing accidents. Final descent and landing of aircraft comprise approximately 3% of the total flight time, while producing 47% of all aviation accidents (O'Hare & Roscoe, 1990). Within this category of accidents, controlled flight into terrain is the leading cause of fatal aircraft accidents world wide (Hansman, Wanke, Kuchar, Mykityshyn, Hahn, & Midkiff, 1992). One such accident occurred near Dulles Airport at Berryville, Virginia, when a Boeing 727 crashed approximately 25 nautical miles northwest of the airport.

The accident occurred during instrumane meteorological conditions while the aircraft was descending. Confusion and misinterpretation of air traffic control (ATC) terminology were contributing factors to this accident. Furthermore, it was obvious from the accident analysis that the maps and approach plates were designed in such a manner that information was not available in a precise and unambiguous form (O'Hare et al., 1990).

As it currently stands, instrument approach procedures create a high workload situation in which the pilot must retrieve information from an approach plate as quickly as possible. Traditionally, approach plate designers have been concerned with forcing as much information onto the approach plates as possible (Taylor, 1976), resulting in excessive clutter and increased time for information retrieval (Hofer, 1993; Kuchar & Hansman, 1993). Pilots complain that it requires too much time to locate the pertinent information on the plates (Cox & Conner, 1987). Additionally, older pilots have difficulty reading the approach plate's small print (O'Hare & Roscoe, 1990). Often, pilots prefer to utilize and rely on other sources of information rather than the instrument approach plates. For example, Hansman and his colleagues found that pilots in their simulation study often accepted Air Traffic Control (ATC) clearances without checking their instrument approach plates to confirm

adequate terrain separation, indicating a general tendency to rely on ATC for terrain clearance (Hansman et al., 1992). Again, this may have been a contributing factor of the Boeing 727's controlled flight into terrain near Dulles. These problems are indications that overreliance on approach plates is undesirable. The current design of paper instrument approach plates is inappropriate or inadequate for terminal area navigation and instrument approach procedures.

Several solutions are available for improving the use of paper approach plates, such as increased cockpit lighting, developing pilot memory skills, and providing training with approach plates (O'Hare et al., 1990). These solutions do not seek to improve instrument approach plates but, rather, to improve the conditions under which they are used. An alternate solution improves the legibility of the plates by increasing the size of their physical features; however, this increases the weight pilots must carry (O'Hare, et al., 1990). A viable option is to declutter the plates by removing nonessential information and by improving the spatial layout of the information on the approach plates (Multer, Disario, Huntly, & Warner, 1993). While all of these solutions may improve the existing paper instrument approach plates, it is possible that the greatest gains may

be achieved by the development of electronic map displays to replace the paper versions.

Like paper maps, electronic maps bring with them a set of design considerations. Once again, the designer is faced with issues of clutter in the displays, best use of the added dimension of color coding (Multer et al., 1993; Hansman et al., 1992), as well as the ideal frame of reference, which will be one of the issues addressed in the current research. In particular, each display may take on either a ego-centered frame of reference (ERF), or a world-centered frame of reference (WRF). The ERF world is analogous to the pilot's view out of the cockpit or a track-up map, while the WRF world is presented as a map in which the canonical alignment is north-up (Aretz, 1988, 1989, 1991; Aretz & Wickens, 1992) and is the perspective offered by current approach plates.

While the issue of fixed versus rotating electronic map displays is one that is already being examined, a more radical design issue for approach plates is whether the plates should be presented in conventional two-dimensional planar format or whether they should be rendered in a three-dimensional perspective format, that might more closely match the pilot's forward field of view through the windscreen and thereby, possibly provide enhanced situation awareness. In the following review of literature, we shall

first address navigation performance issues in comparing two- with three dimensional displays and will then address the issue of map rotation.

3D Displays

The advancements in technology featuring the increased speed of computer graphics software and hardware have enabled the design of three-dimensional displays which, by more closely resembling the domain of objects and events they are meant to depict, provide more "natural" viewing conditions. In order to accomplish this, the display must convince the perceptual system that a third, or depth, dimension exists. The most commonly employed method of achieving this illusion is to incorporate into the display some pictorial "cues to depth." Wickens, Todd, Seidler (1989) provide a thorough review of depth cues and their interactions. The most common depth cues that are often incorporated into three-dimensional displays include linear perspective, texture gradients, relative size of similar objects, size of familiar objects, height in the visual field, interposition, and motion parallax (Haskell et al., 1992).

The justifications for designing three-dimensional displays are two-fold. First, to an operator who typically views the world from other than a top-down perspective (Roscoe, 1968) the visual scene of the three-dimensional

world is a more "natural" or "compatible" representation, than is that provided by a two-dimensional display. Second, a single integrated representation of one object or scene reduces the need for mental integration of two or three planar representations (Wickens et al., 1989). The idea that integrated displays support integration tasks has been validated by a number of studies in the literature, summarized by Wickens (1992; see also Bennett & Flach, 1992). Indeed this relation between display and task integration is one key element of a design principle called the Proximity Compatibility Principle (PCP; Wickens, 1992). The other element of the PCP is an assertion that the conditions of integrated display that help integration tasks may hurt (or at least, will not help) those tasks that require the focused attention on a single component of the integrated dimensions.

The PCP can be tied directly to aviation, in which flight control is considered an integration task. Pilots must comprehend and integrate the three dimensions of location (lateral, vertical, and position along course) and the rate of change along these dimensions (heading, rate of climb, and airspeed) in order to establish and maintain effective flight control. However, flying is also characterized by the need to make precise readings along certain axes, such as the vertical separation of aircraft

(Haskell & Wickens, 1993). Thus, the PCP provides some help in determining under what conditions three-dimensional displays should be used (Wickens, 1992). The PCP predicts that a three-dimensional display will be superior for the integrative characteristics of flight control, but this advantage may be reduced or eliminated for tasks requiring attention to be focused on a single axis. In the following, we first review studies that investigate the utility of three-dimensional displays, and then we consider those studies which compare three-dimensional displays with more conventional two-dimensional displays presenting equivalent information.

For consistency, the following review of the literature refers to the term "three-dimensional" as any display that attempts to spatially represent a depth dimension by incorporating cues to represent depth along the viewing axis. Stereoscopic presentation is only one among many cues that can be used in this endeavor. Two-dimensional displays are those that do not make any attempt to present depth information.

Conventional aircraft displays and instruments are two-dimensional in design. These displays and instruments have proven their utility for flight control over a number of years. However, radical designs that integrate information into one "natural" or "compatible" display, such as a three-

dimensional display, are fairly revolutionary. These displays should be evaluated in order to discover their utility for flight control and situation awareness prior to being integrated into the aviation cockpit.

Wickens, Haskell and Harte (1989) conducted a study in which twenty-four subjects flew a computer-simulated transport aircraft during final approach using two different three-dimensional perspective tunnel displays. While many factors were manipulated in this study, the relevant results indicate that the pilots performed the landing task effectively using either display, even during disturbances such as simulated wind shears and display failures. This study shows the utility of three-dimensional displays.

Another study drawing similar conclusions administered by Barfield, Rosenberg, Han, and Furness (1992) examined two perspective displays for target location. Thirteen subjects flew a simulated F-16 over a computer-simulated flight environment to intercept a series of "pop-up" targets. While the data indicated superior flight path performance with one of the displays, the pilots were able to effectively perform the task using either of the perspective displays.

A study by Wempe and Palmer (1970) indicated opposition to the findings of the previous studies. They showed that three-dimensional displays did not support effective

performance for the task of landing aircraft. While the runway displays were presented in perspective, they incorporated very few additional depth cues, leaving only an ambiguous outline of a runway. Due to the insufficient use of depth cues, pilots had difficulty judging altitude, rate of approach, rate of descent, and distance from the runway. While performance on the landing task was poor, the implementation of display aids to assist the pilot may have produced different results.

Comparison of 2D and 3D Displays

Considering the number of studies that endorse the utility of three-dimensional displays, one might conclude that their implementation in future aviation displays is inevitable. This, however, is not the case. There are few studies that actually compare three-dimensional displays to equivalent two-dimensional displays, begging the question of three-dimensional display costs and benefits. Furthermore, it appears as though these existing comparisons fall into one of three separate categories. One category is the comparison of two- with three- dimensional displays involving monitoring and locating objects in an airspace. A second category evaluates the comparison between two- and three- dimensional display types for purely navigation tasks through simulated worlds. A third category evaluates two- and three- dimensional displays in the context of a

combination of navigation and situation awareness tasks. This section reviews each category of studies which compares three- and two- dimensional displays in an aviation context.

Monitoring and location identification. Several studies have compared two- and three- dimensional displays for tasks that require monitoring of aircraft in an airspace and identifying their locations. These studies are open loop and have required little or no navigation on the part of the subjects. For example, Ellis, McGreevy, and Hitchcock (1987) conducted a study comparing two cockpit displays of traffic information (CDTI). Each display presented the pilots with the location, altitude, and heading of their aircraft, and the heading of other aircraft within a certain range of their own aircraft. One display was a two-dimensional, top-down horizontal display. The other display was three-dimensional, showing the pilot's own aircraft from slightly behind, above and from the right. The pilot's tasks were to monitor the aircraft on the display, identify potential collision hazards, and to select evasive maneuvers when deemed necessary.

The results indicated that hazard identification was better supported by the three-dimensional display than with the two-dimensional planar display. The pilots were more accurate in their judgements of when evasive maneuvers were necessary. In addition, the pilots used more altitude

changes to avoid collisions than with the two-dimensional representation, in which they relied on lateral maneuvers to evade potential collisions. The two formats were not entirely equivalent, however. Even though the same information was displayed in both formats, the altitude on the two-dimensional display was represented alphanumerically rather than spatially. If an alternative two-dimensional display was designed with spatial representation of altitude, the differences between the two formats may not have occurred.

Bemis, Leeds, and Winer (1988) compared two tactical aviation displays used for air intercept control. As in Ellis, McGreevy, and Hitchcock's study, a two-dimensional top-down horizontal situation display and a three-dimensional display were compared. The two-dimensional display depicted the lateral position of the aircraft while altitude was determined by requiring the subject to "hook" the aircraft symbol as in actual tactical displays. The three dimensional display used perspective cues to depth, allowing the subject to hook the aircraft symbol in this format to obtain precise altitude information or to obtain approximate altitudes and relative altitude information directly from the display. The subject's task was to detect aircraft that posed a pontential threat and then to select the closest interceptor aircraft for each threat.

The results demonstrated that the subjects detected the threat aircraft more accurately with the three-dimensional display while also providing increased accuracy and quicker selection time of the closest interceptor aircraft. While the depth cues in the three-dimensional display were sparse, it provided better task performance than the two-dimensional display. This study, in conjunction with the previous study by Ellis and his colleagues, indicates that the three-dimensional map better supports the tasks of monitoring aircraft, detecting hazards, and locating objects in three-dimensional airspace.

One study that did not agree with the findings of the previous studies was carried out by Tham and Wickens (1993). This study was conducted in two phases, using air traffic controllers, pilots, and novices to compare performance with a perspective ATC display to a conventional plan view display. In phase one, the subjects were given numerous tasks to complete serially, including: heading judgment of an aircraft, vectoring of an aircraft to a desired location, identification of the highest aircraft, identification of the fastest aircraft, and the identification of potential conflicts between aircraft. The results from phase one of the experiment showed a benefit for the judgment tasks along the orthogonal, vertical, and lateral axes for the plan view display while indicating no difference between the two

displays for conflict identification, the only task that involved the integration of lateral and vertical dimensions. Phase two of the experiment was conducted using only the air traffic controllers and the best performing pilots from the first phase. The subjects were given a task similar to what would be expected in a "real" ATC environment. Equal efficiency in traffic management was found between the two display formats. Furthermore, all other measures showed equivalent performance except that subjects with the perspective view were slower in detecting unanticipated aircraft heading changes. The findings of this study counter those of the previous two studies. There appears to be a need for further evaluation in this area, in which display scenes change and update relatively slowly.

<u>Navigation through simulated worlds.</u> Wilkens and Schattenmann (1968) compared pilot performance on flight path tracking accuracy using three different displays. One display was three-dimensional incorporating few depth cues: motion and linear perspective. The scene depicted a perspective runway created by bright runway lights and a runway centerline. The display also incorporated a moving horizon and the addition of a flight director indication of the command path. A second display was a two-dimensional flight director display while the third was a standard instrument landing system (ILS) instrument array, with a few

minor adjustments. The subjects flew simulations with the control dynamics of small single engine propeller aircraft and single engine jet fighters. The results indicated that there was an advantage for the pictorial displays over the standard ILS format. The only difference between the two- and three- dimensional formats occurred in the most difficult condition, which consisted of landing the aircraft in a crosswind. In this condition, the three-dimensional representation was superior to the two-dimensional display. Although the depth cues implemented into the three-dimensional display were limited, the study demonstrates that displays incorporating even a few depth cues are better for aircraft flight control and navigation than displays with depth cues absent.

Grunwald, Robertson, and Hatfield (1981) compared several "highway in the sky" displays, incorporating preview and prediction, for landing helicopters through three-dimensional curved landing approaches. One display was a traditional cockpit display, and the remainder of the displays were variations of three-dimensional perspective. The performance measures were flight path tracking accuracy and a secondary monitoring task. The results indicated that the three-dimensional displays supported superior flight path tracking accuracy relative to the two-dimensional display. However, only four pilots were used in this study;

therefore, the results were not analyzed statistically, presenting difficulties in generalizing this study's results to other three- versus two- dimensional comparison studies. Despite its statistical weakness, this study in conjunction with Wilkens and Schattenman's study indicate a strong case for three dimensional displays for flight control.

Simultaneous monitoring and control. Neither monitoring/identification tasks nor flight control navigation tasks alone are adequate to fully evaluate the utility of three-dimensional displays. Both tasks need to be examined simultaneously for full revelation of the differences between two- versus three- dimensional displays. One such study, conducted by Haskell and Wickens (1993), compared two displays incorporating both prediction and preview. One display consisted of three two-dimensional orthogonal spatial views while the other display presented a three-dimensional, inside-out, perspective view. The performance measures were flight path tracking accuracy during routine and disrupted flight, and reaction time and accuracy to judge the location and trajectory of other airborn targets. The results demonstrated superiority in lateral and vertical flight control for the three-dimensional display while airspeed tracking accuracy was better supported by the two-dimensional display. Furthermore, there were no consistent differences in the

judgment task as a result of display type. This study indicates that the three-dimensional display is a viable option for aviation cockpits and supports the past assertion that lateral and vertical flight control tasks are performed better using three-dimensional displays. Yet this study leaves open the question of how situation awareness is effected by display type.

Many of these studies indicate the advantage of three-dimensional displays over their two-dimensional counterparts. In contrast to the previous study by Haskell and Wickens (1993), an investigation conducted by Andre, Wickens, Moorman, and Boschelli (1990) did not find an advantage for three-dimensional displays. This study compared two different display formats. One display was an outside-in three-dimensional representation of the complete airspace, and the other display presented an equivalent two-dimensional array of instruments. Subjects flew a low fidelity simulation of a fixed wing aircraft to several waypoints using one of these displays. Flight control was better supported by the two-dimensional display than by the three-dimensional display. The authors attributed this finding to the inherent ambiguity along the line of sight created in the three-dimensional display as subjects flew closer to the navigation waypoints.

The studies addressed in this review did not fully evaluate the differences between the two- and three-dimensional formats. Most of the performance measures were those of integration tasks, in which theory suggests, and data has supported, superior performance for three-dimensional displays. Relatively few non-integration or focused attention tasks were evaluated, or the results were inconclusive. While Tham and Wickens explicitly examined such focused attention tasks, this evaluation was done in the context of Air Traffic Control, not flight control. Furthermore, none of the studies have explicitly examined how display dimensionality influences performance in following airport approach plates.

Display Rotation: The Frame of Reference Issue

Instrument approach plates and maps are traditionally printed and viewed in a north-up fashion (from a WRF), yet the pilot's control axes over the aircraft is "left-right" (ERF) not "north-south." Hence, mental transformations may be required by the pilot to align the WRF view of the map with the ERF view of flying. One of these transformations is mental rotation.

The cognitive operation of mental rotation is required to achieve the alignment of the world-center frame of reference with the ego-centered frame of reference (Aretz, 1991). Data indicate that it is a fragile and mentally

demanding process and is not used when the comparisons between ERF and WRF become difficult (Aretz & Wickens, 1991). This process can be eliminated by providing the pilot with a rotating or track-up map.

Shepard and Metzler (1971) provided the first mental rotation experiment in which they showed that the time required to compare two visual images increased linearly with the angle of disparity between the images. Shepard and Cooper (1982) proposed that mental rotation of visual images is analogous to the corresponding physical rotation that would occur with an actual object.

Similarly, studies conducted by Aretz (1988, 1989, 1991) extended the theory of mental rotation from visual objects to visual scenes and maps. These studies show that if standard north-up alignment does not match the direction of travel, mental rotation must be performed to bring the WRF into congruence with the ERF (Aretz, 1988, 1989, 1991, Aretz & Wickens, 1992). Again, however, if a map can be rotated to a track-up alignment, mental rotation is no longer required. The rotating track-up map's axis of "up" on the map is consistently aligned with the forward field of view (FFV). Therefore, left-right judgements on the map will always be congruent with those in the FFV (Wickens, 1992), and this congruency is compatible with the pilot's manual flight control. Alternatively, one must consider the

compatibility of the display appearance with the pilot's mental model of the way the aircraft moves through the world (Wickens, Haskell, & Harte, 1989; Hansman et al., 1992). The pilot's mental model is that of a fixed world and a moving aircraft (Johnson & Roscoe, 1972), which would suggest that a fixed map is better; therefore a fixed map should lead to enhanced pilot performance as well as enhanced decision making. As a result, we have two principles in vehement opposition.

Wickens, Haskell, and Harte (1989) compared flight path performance and situation awareness as pilots flew approach paths to North American airports using either an inside-out (ERF) display or an outside-in (WRF) display. Both displays in their experiment were three-dimensional forward looking and, therefore, "track-up" displays. However, they differed in terms of whether the aircraft symbol moved on the display frame (WRF) or the depicted world moved (ERF). The data indicated that flight path performance using the inside-out display was superior; however, there was no difference between the frames of reference in terms of measures of situation awareness. This study seems to suggest that ego-centered frames of reference are more advantageous for pilots.

Data from several other studies that have compared fixed north-up and rotating track-up two-dimensional maps

indicate no conclusive advantage of one design over the other. Mykityshyn and Hansman (1990) were not able to draw firm conclusions as to the relative benefits of one frame of reference over another despite the fact that pilots favored the fixed north-up format. Aretz (1991) found that the track-up map simplified flight controls, where all turns were left or right of the aircraft's current heading, providing congruence between the map and the world. On the other hand, the north-up map supported better performance for world and map reconstruction.

Another study conducted by Harwood and Wickens (1991) used a computer generated map display for Nap-of-the-Earth (NOE) and low-level helicopter flight to compare different display frames of reference. The north-up map supported the location of objects, which is characteristic of the world-centered reference frame, while the track-up map provided better performance on tasks that required map-terrain congruency characteristic of the ego-centered reference frame. These findings indicate that there are map-task dependencies which are supported to varying degrees by different frames of reference. Harwood and Wickens concluded that a configurable map display, with fixed north-up orientation used most of the time, as well as a pilot-selectable option available so that the map could be aligned

with the environment when navigation requirements or pilot preference changed, could be advantageous.

Barfield, Rosenberg, Han, and Furness (1992) investigated pilot flight performance and situation awareness using displays with differing frames of reference. Their data indicated that the pilot's eye (ERF) display was superior to the God's eye (WRF) display for flight control resulting in shorter distances flown between targets. However, the God's eye display was superior for map reconstruction, indicating enhanced situation awareness. This study supports the findings of previous studies which indicate map-task dependencies.

While these studies are not in complete agreement, there seems to be a strong indication that maps formatted in an ego-centered reference frame support flight control tasks while maps implementing the world-centered reference frame support situation awareness. This investigation of map-task dependencies is crucial for the design of instrument approach plates, especially when the added design consideration of two- versus three- dimensional representation are introduced. Traditionally, two-dimensional displays have been the format used in an aviation context; however, it now becomes necessary to focus on design implications for the more radical display formats characteristic of three-dimensional displays.

3D Design Implementations

Three-dimensional displays, designed for use in the aviation setting, require a number of considerations and specific design decisions in addition to the issue of what monocular depth cues are incorporated in the display. The following section addresses some of these considerations, which impact the design of three-dimensional displays.

Fidelity. Even though three-dimensional displays provide a more "natural" or "compatible" scene for the pilot, there is not enough evidence to validate their effectiveness relative to equivalent two-dimensional displays across all tasks. Evidence seems to indicate that the benefits attributed to each of the displays are relatively task-dependent. An obvious consideration, then, is the expense of three-dimensional designs.

Three-dimensional displays require greater computer hardware and software power over the two-dimensional displays due to their enhanced graphics. Also, in order to rotate a three-dimensional display, the computer must have greater speed in order to update the display in "real time." It is increasingly difficult, computationally, to rotate three-dimensional displays because the terrain features look different from each ego-centered view point (Wickens, 1992). One option, then, is to simplify the three dimensional

version of the display. Schematics or symbols could be used in lieu of the realistically shaped and textured terrain features.

Emphasizing this point is a study conducted by Williams (1993) examining the effect of scene detail on pilot flight control performance. The factor of scene detail did not affect either horizontal or vertical flight performance. For a pure navigation task, as long as the schematic features are easy to identify and comprehend, scene detail does not appear to be a critical factor, and low levels of scene detail can be effectively implemented in displays (Williams, 1993).

During navigation, pilots can perceive their bearing and range to their "target," and the navigation task only requires the display to provide adequate discrimination between landmarks. This scene simplification decreases the computer power required while providing the pilot with adequate "natural" scenes for enhanced performance. However, scene detail is important for landing approaches, when pilots need precise depth cues of slant, texture, among others, in order to accurately land an aircraft (Lintern & Walker, 1991).

Field of View. A second consideration in the design of three-dimensional displays is the field of view (Barfield, Rosenberg, Han, & Furness, 1992). The field of view of an

aviation display is defined with respect to a pilot's viewing distance from the display (Wickens, 1992). Field of view can be either veridical, telescopic, or wide angle.

The veridical field of view is one in which the landmarks on the display are positioned where they would be if the pilot were looking out the cockpit, "through the display" at the actual terrain. The telescopic field of view is a narrower view, creating a scene magnification, while the wide angle view depicts a wide scene representation, thereby minifying the three-dimensional display scene (Wickens, 1992, Barfield et al., 1992).

As the scene viewing angle is either widened or narrowed from the veridical view, the one-to-one correspondence of angles between the display terrain features and those between the real world terrain features is lost (Wickens, 1992). This issue, of an optimal field of view, is far from being resolved. The data from a recent study comparing two different three-dimensional displays conducted by Barfield and his colleagues indicated that flight path performance (shortest distance between targets) was better for a 30 degree geometric field of view than for two wider fields of view, 60 and 75 degrees. These findings suggest that scene magnification enhances performance relative to the minification of the same scene (Barfield et al., 1992). This study supports other arguments made for

scene magnification to compensate for the tendency of pilots to perceptually "minify" the display scene (Roscoe, 1981).

While perceptual minification of three-dimensional displays seems to indicate a problem in designing for the optimization of global planning and situation awareness, a fully magnified field of view only allows the pilot to see that which is directly in front of the aircraft. This makes for a very poor map display because it does not provide knowledge of feature and landmarks all around the pilot (e.g., the ability to visualize a missed approach path), which are typically available in the two-dimensional approach plate.

Viewing Angle. A third important consideration in the design of three-dimensional displays is the elevation angle relative to the ground plane (Wickens, 1992). This design parameter can be made alterable, but there is a danger in the lack of consistency supported by the display at different viewing angles.

Some data suggests that a viewing angle of 30-45 degrees is best (Eley, 1988, Kim, Ellis, Tyler, Hannaford, & Stark, 1987). Wickens (1992) proposes that this is the range of viewing angles over which the shape of the terrain features on the display correspond to their shape in the world while the separation of the actual terrain in the distance is represented by proportional separation on the

display. Barfield's study, mentioned previously, suggests that a viewing angle of 60 degrees is superior to a 30 degree eyepoint elevation (Barfield et al., 1992). The authors found that the more top down view was superior yet it lost its effectiveness as it reached a 90 degree viewing angle (eg. planar display).

It is proposed that viewing angles that are too high degrade the correspondence between the display and world terrain features while low viewing angles eliminate the proportionality of viewed terrain separation angle and actual location angle (Wickens, 1992). It seems that this parameter requires further investigation to determine an optimal viewing angle for three-dimensional displays.

Viewing Distance. A fourth and final issue concerning three-dimensional display implementation is viewing distance. This issue becomes significant when deciding how to implement viewing distance in a rotating ego-referenced three-dimensional display depicting the pilot's aircraft within the airspace. Two competing options are the "tether" view and the "track" view. The tether view is one in which the viewing distance is held constant trailing the aircraft as may be the view seen from a chase plane or drone that is "tethered" behind the aircraft at a constant distance. This distance parameter can be made changeable to a desired experimental setting. While the viewing distance is held

constant with the tether view, problems arise in the depiction of the forward field of view. A viewing distance too close to the aircraft would reduce the world scene represented in the display while far viewing distance reduces the size of the display's features, making it difficult to discriminate landmarks and terrain hazards.

An alternative to the tether view is the track view. The track view is depicted as a camera that follows directly behind the aircraft yet is on a "circular track" around the outside of the simulated world. Its position on the track corresponds to the pilot's momentary heading so left-right from the pilot's cockpit corresponds to left-right on the map view. The aircraft would appear closer as it was near the camera edge of the display while becoming increasingly distant (and smaller if perspective geometry is used) as it flew towards the far edge. Because the pilot's aircraft will be viewed from different distances, the track view allows the entire world to be visible at all times, thereby allowing for maximum viewing area. However, because the perspective distance to the aircraft changes, the track view may be more susceptible to perceptual ambiguities in depth judgment along the line of sight than the tether view, especially when the aircraft is perceived to be further away from the pilot.

Experimental Rationale

It is clear from the previous discussion that there exist few effective theory-based comparisons of a three-dimensional perspective flight display with a two-dimensional display containing equivalent information. However, the results of those studies that were available revealed that three-dimensional displays were better for flight path control (e.g., Wilkens et al., 1968; Grunwald et al., 1981; Haskell et al., 1993), but ambiguities in distance judgments sometimes caused problems in precise spatial localization (e.g., Andre et al., 1990; Tham et al., 1993).

Also, collectively, the ego-centered frame of reference was found to be best for navigation tasks, but the word-centered reference frame may be better for situational awareness. Furthermore, the study and displays of Hansman et al. (1992) were designed or implemented as solutions for display frame of reference, and this was done in a "pilot study" that did not contain extensive, statistically reliable performance data. Finally, the potential interactions between the two factors of dimensionality and frame of reference are unknown because previous studies have not evaluated the two factors of dimensionality and frame of reference in a complete orthogonal design. It is necessary to investigate this interaction because any design that is

implemented into future cockpit displays must effectively enhance flight control and situation awareness.

The study reported here addresses two main issues with regard to pilot approach charts. The first is a comparison of the relative merits of map dimensionality--a three-dimensional view versus an otherwise equivalent two-dimensional display--for the integrated task of flight control and for situation awareness. The second is an examination of display frame of reference, fixed north-up (WRF) versus rotating track-up (ERF).

METHOD

Subjects flew eight landing approaches in one 2 hour session, using either a fixed north-up or rotating track-up display represented in either a two-dimensional planar or three-dimensional perspective view. In addition, subjects were required to report the position and height of the nearest terrain hazard to assess the utility of each condition for situation awareness.

Subjects

Thirty subjects, 25 males and 5 females, were paid $5.00 per hour to participate in this experiment. The subjects were enrolled in Aviation 120, a second semester course for private pilots, at the University of Illinois, Urbana-Champaign. Students had minimal experience with instrument approach plates. All subjects reported a visual acuity of 20/20 or better (corrected/uncorrected). Subjects' ages ranged from 18 to 24 years with a median of 20 years.

Independent Variables

This study manipulated three independent variables. One between subjects variable and two within subjects variables were evaluated. Two groups of subjects flew eight approaches using either a fixed north-up or rotating track-up display. Four of these approaches for each group were flown in each of a two-dimensional and three-dimensional

representation of the world. The third variable was the direction of navigation along the approach path. Each approach was divided into northerly and southerly legs.

Dependent Measures

Root mean square error (RMSE) was collected for both the lateral (ground track) and vertical (altitude) flight control performance for all four approach paths in the two- and three- dimensional worlds. The RMS error was collected separately for both the straight leg and turn sections of the approach paths. The horizontal error was the deviation from the ideal ground track while the vertical error was the deviation from the ideal altitude as indicated by the altitude path or "sky track". Error was sampled at a rate of 2 cycles per second, and the mean RMS for each leg was automatically calculated and recorded by the simulation program.

Two additional dependent measures, latency and error, were obtained from the subject's position reports. Response latency was a measure of the time required by a subject to locate and respond to the position of the nearest terrain feature. Response error for the ego-centered response was the absolute difference between the reported and ideal response in whole "clock" units. The world-centered response error was the absolute difference in degrees between the reported and ideal responses. Height error was

the difference between the reported and ideal response considering the responses as units on an interval scale.

Apparatus and Displays

Equipment. This study was conducted on a Silicon Graphics Iris Workstation with a 16 inch diagonal screen. The subjects were seated in a chair with a two degree of freedom joystick attached to the right arm of the chair. The joystick controlled the vertical and lateral deviations of the aircraft. Pushing forward would pitch the aircraft down while pulling back on the stick would make the aircraft pitch up. Pitch angle controlled the rate of change of altitude. Similarly, a left movement of the joystick would bank the aircraft left, and a right movement would bank the aircraft right. Bank angle controlled the rate of change of heading.

The subjects were allowed to move the chair to a comfortable sitting and viewing distance from the screen. While this distance was not controlled, the variable distance was small between subjects. Cockpit seats are somewhat adjustable, so seating distance was an irrelevant factor in the experiment.

Two-Dimensional Display. The two-dimensional world consisted of two separate displays presented on one computer screen (see Figure 1). The top display was a planar map indicating the lateral (x-z) position of the aircraft along

the approach path, and the bottom display indicated the aircraft's altitude (y) on a vertical profile of the landing approach path.

The two-dimensional display was presented in either a fixed north-up format where the world is static or a rotating track-up format in which only the top display rotates while the vertical profile remains static.

The planar map included brown geometric shapes (ie. rectangles, circles) indicating the location of terrain features. A brown line indicated the ideal approach path through the world while a white icon of an aircraft represented the location of the pilot's ownship along this approach path. A white arrow with an "N" was always displayed in the northwest corner of the map for directional reference. Also, an attitude indicator was located in the center of the display to aid the subject's flight control. The attitude display indicator incorporated a moving horizon while the aircraft remained fixed.

The vertical profile positioned below the planar display represented the aircraft's altitude from left to right along the approach path. The profile pictorially indicated the level and descent flight segments of a particular approach. A white icon of an aircraft indicated the aircraft's actual altitude in respect to the ideal altitude along the approach path. The terrain feature's

height was also represented on the vertical profile. The wire-frame features in front of the approach path indicated terrain to the right of the aircraft as represented in the top display while the solid features behind the approach path indicated terrain features to the left of the aircraft. Some terrain features were distorted in their position along the horizontal axis to emphasize that these terrain features posed a threat during a particular turn along the approach. Their altitude was not distorted in any fashion.

Three-Dimensional Display. While the two-dimensional display incorporated two separate display panels, the three-dimensional map pictorially depicted the same information in one integrated display, implementing either a fixed north-up or rotating track-up frame of reference (see Figure 2). Although this display was depicted on a two-dimensional surface, it incorporated depth cues, such as linear perspective, interposition, motion parallax, size of familiar objects, and height in the visual field, enabling the subject to perceive a third dimension, depth. In addition, grid lines on the display were visible, aiding in the perception of linear perspective. The viewing elevation angle of the projected scene was 29 degrees while the field of view was 68.4 degrees.

The three-dimensional world contained geometric figures (ie. rectangular cubes, pyramids, cones) representing

terrain features. The terrain features were brown on a green plane (x-z). The approach path was indicated by both a black ground track and a light brown "sky track" connected to the ground track by posts at turns and altitude changes. An aircraft icon with white nose and red tail followed along the "sky track" while its black shadow indicated the aircraft's lateral deviation from the ideal path. The size of the aircraft became smaller as it was perceived to be moving further away from the subject's viewing position. A white arrow with an "N" at its point was always presented in the northwest corner of the display for quick directional reference. This directional indicator was absent only for very infrequent occasions in the rotating map condition and was always visible during the probes for situation awareness. In addition, an attitude indicator was superimposed in the middle of the map scene so as to aid subjects with flight control while not obstructing the terrain, aircraft, or path.

Map Frame of Reference. Each of the display types mentioned above could be implemented in either a static or dynamic format. The static format, which was the same for both the two- and three- dimensional conditions, was a fixed north-up map in which the aircraft translated through its static environment. The dynamic condition was rendered by using a rotating track-up map in which not only does the map

rotate but the aircraft translated through the world. The difference between the two- and three- dimensional conditions was that the entire map rotated in the three-dimensional condition while only the top display rotated in the two-dimensional condition, and the vertical profile remained static. In the three-dimensional rotating map condition, the viewpoint was always behind the aircraft since it was depicted from the border of the map, but it encompassed the whole simulated region, thus implementing the "track" view concept rather than the "tether" view.

Landing Approach Paths. The landing approach paths were presented in either of two unique worlds, differing in number and location of terrain features. Two paths displayed separately, one originating in the north and the other in the south, were in one world, and the other two paths, originating in either the north or south, were in another world. Hence, four different scenes in each of a two-dimensional and a three-dimensional display were used by the subjects. The path presentation was counterbalanced to control for learning affects.

Each path represented a landing approach path for terminal area navigation. On an average, each approach plath was 27 miles in length and required approximately 10-15 minutes to fly. Furthermore, each path contained exactly five level flight segments and 5 segments in which the

aircraft must descend. The number of turning segments varied for each of the four approach paths (e.g., 5, 4, 8, 7, respectively) and occured only during level flight. Both the two- and three- dimensional displays provided a ground track for lateral guidance along the ideal path; however, a vertical profile was provided in the two-dimensional condition to provide altitude information while the three-dimensional condition implemented a "sky track" for the same information.

Flight Dynamics. The aircraft's flight dynamics were not intended to simulate any particular aircraft. The flight controls were designed so that bank and pitch were first order controls leading to the second order controls of heading and of altitude. The aircraft's airspeed was held constant at 85 knots for simplification of the flight control task. Furthermore, the program was designed to only allow for 60 degrees of bank and +/- 20 degrees of pitch, eliminating the possibility of inverted flight which would not happen at speeds this low. There was no rudder control implemented in the flight dynamics, so turns were controlled strictly by bank angle. There were no disturbances (ie. windshear, turbulence) during the flight, yet the task was such that the subjects had to pay reasonably close attention to flying the aircraft while minimizing flight path error.

Tasks

Subjects were given two primary tasks: fly the aircraft to minimize flight path deviations and answer questions related to measures of situation awareness. Subjects manuevered the aircraft by the use of a joystick, which directly controlled pitch and bank, and thereby reduced heading and altitude deviations. Twice during each of eight landing approaches, the subject was probed for the nearest terrain feature and was required to give three separate responses. Subjects were required to verbally indicate the position, in both ego-centered (o'clock) and world-centered (absolute degrees) terminology, and height (high, same, low) of the nearest terrain hazard with respect to the aircraft as quickly and accurately as possible. Upon hearing the ego-centered response and height, the experimenter simultaneously recorded the position response and depressed a key that caused the computer to record the response latency. The same thing occurred after the subject gave the world-centered response. The WRF response latency began recording from the time the experimentor recorded the ERF/height response latency. This response order was emphasized to the subject.

Design and Procedure

The subjects were divided into two groups of fifteen for assignment to the map frame of reference condition; that

is, each group was presented with either the fixed north-up or the rotating track-up condition. Each subject flew eight landing approaches, four with the two-dimensional display and four with the three-dimensional display. Display order was conterbalanced such that half of the subjects in each frame of reference group flew the four three-dimensional approaches first, and half flew the four two-dimensional approaches first. Each approach was encountered twice, once in the two-dimensional map and once in the three-dimensional map. Finally, each approach consisted of both northbound and southbound legs.

Upon arrival to the laboratory the subject was asked to complete the necessary consent forms and a bibliography information sheet consisting of questions regarding the subject's age, visual acuity, sex, and preferred hand (left or right). Following the completion of these forms, the subject was handed a subject briefing describing the individual's participation in the experiment. The briefing described the frame of reference condition the subject would view and then provided simplified drawings of the two- and three- dimensional worlds. Additionally, the subject was given an example of the judgment task which would be required during the landing approach.

The experimenter was present to answer any questions, resolving any ambiguities concerning the flight stick

sensitivity, flight control task, or judgment task. This question and answer session was emphasized because there were no practice sessions before actual data collection. The subject was then isolated in an experiment room to continue with the experiment. The lighting in the room was turned down to reduce any glare on the display screen. Also, the subject was informed that the chair could be moved to a comfortable position.

The experiment began when the subject was prepared and continued at each subject's own pace, allowing for breaks between landings if necessary. Upon completion of the first four approaches, the experimenter down-loaded the display type not yet seen, and the subject flew four approaches in this new world.

Upon completion of the experiment, the subject was given a questionnaire containing questions eliciting preferences between two- and three- dimensional display types, difficulty of control and judgments in each display, and any additional comments. Finally, the subject signed the payment form, received enumeration, and was dismissed.

RESULTS

Overview

Repeated-measures mixed analyses of variance were performed on flight control root mean square (RMS) error and judgment task response latency and error as these were effected by three variables of interest: map dimensionality, map frame of reference, and direction of flight (north or south). The analyses performed on flight control RMS error pooled the sums of variances between subjects, replications, and flight legs because the assumption was made that they were equal, and this accounted for the large degrees of freedom in the analyses. Map dimensionality and direction of flight were within-subjects variables while map frame of reference was varied between subjects.

Flight control RMS error was collected separately for lateral and vertical deviations from the ideal approach path during both straight segments and turn segments of flight along the approach path. For the judgment tasks, response latency was collected for responses of o'clock position with height (ERF judgment) and absolute bearing response (WRF judgment) of the nearest terrain feature. Judgment task error was collected for the same three responses, individually.

Flight Path Performance

Lateral RMS. As shown in Figure 3 which depicts lateral error along straight segments, the analysis indicated that there was a significant main effect on flight path performance for map dimensionality $F(1,358)=48.853$, $p<.001$. Subjects were able to control lateral deviations with respect to the ideal approach path more effectively with the two-dimensional display than with the three-dimensional display. Furthermore, the analysis identified a significant advantage for the rotating map frame of reference on lateral RMS, $F(1,358)= 43.563$, $p<.001$. The direction of travel on lateral RMS shown in Figure 4, significantly influenced lateral flight control during straight flight, $F(1,358)=4.821$, $p<.05$, where subjects controlled the aircraft's lateral movements better while flying in a northerly direction. The apparent interaction between direction of travel and map rotation, indicating a greater cost for fixed maps on southbound legs, was not significant, $F(1,358)=.116$, $p=.733$.

Lateral RMS showed the same pattern in turns as in straight flight which was depicted in Figure 3. A significant cost to the three-dimensional map on lateral RMS was indicated during turns $F(1,358)=61.591$, $p<.001$. In addition, a significant effect of frame of reference influenced lateral RMS during turns, $F(1,358)=31.816$,

$p<.001$. Once again, superior flight path performance was supported by the rotating track-up map. While direction of flight influenced lateral RMS during straight flight, it had no significant influence on lateral RMS during turns, nor did flight direction interact with frame of reference.

Vertical RMS. Vertical RMS, as shown in Figure 5, was significantly influenced by map dimensionality during straight flight, $F(1,358)=255.212$, $p<.001$. As was the case with lateral RMS, the two-dimensional display supported better vertical flight control performance. No significant effects of frame of reference or direction of travel on vertical RMS during straight flight were present. Figure 5 also shows a significant two-way interaction between map dimensionality and frame of reference on vertical flight control during the straight flight, $F(1,358)=9.031$, $p<.01$. The interaction depicts better vertical flight control for the two-dimensional display in the rotating track-up frame of reference than in the fixed north-up frame of reference. The opposite was true for the three-dimensional display where the fixed map provided for more effective control while performance was degraded for the rotating track-up map.

The effects of map dimensionality on lateral RMS during turns, $F(1,358)= 284.920$, $p<.001$, also indicated better vertical control using the two-dimensional display than the

three-dimensional display just as the pattern for straight flight shown in Figure 5. The effects of frame of reference and direction of travel on vertical RMS during turns were nonsignificant. A significant two-way interaction between map dimensionality and frame of reference on lateral RMS during turns, $F(1,358)=11.799$, $p<.001$, displayed the same pattern, an advantage for the rotating frame with the two-dimensional maps and cost with the three-dimensional maps, as the interaction between these same variables for straight flight as shown in Figure 5.

Situation Awareness

Response Latency. Map dimensionality did not have any effect on the latency to give a clock heading to the nearest terrain feature (ERF response). Figure 6 shows that the rotating track-up map tended to support quicker ERF response times although this advantage was confined to the two-dimensional display with the analysis indicating a marginally significant main effect of map frame of reference on ERF reaction time, $F(1,118)=6.355$, $p=.085$. Direction of travel had no significant influence on ERF response latency.

The analysis indicated that there were not main effects of map dimensionality, frame of reference, or direction of travel on WRF response latency.

Response Error. The effects of map dimensionality on ERF response bearing error indicated that errors were

reduced by half with the two-dimensional display $F(1,112)=9.808$, $p<.01$. The data indicated that there were no signigicant main effects of frame of reference or direction of travel on ERF response error.

The effect of map dimensionality on height judgment error was also significant, $F(1,111)=64.288$, $p<.001$. The two-dimensional display supported better performance for height judgments than the three-dimensional display. Frame of reference had no significant influence on height judgment error. The effects of direction of travel on height judgment error shown in Figure 7 indicated that pilots reduced these errors when heading in a northerly direction, $F(1,111)=30.277$, $p<.001$. The effect of rotation was nonsignificant; however, a significant two-way interaction shown in Figure 7 between direction of travel and map frame of reference indicated that there was a greater cost for the rotating display when flying south than for the fixed display, $F(1,111)=4.662$, $p<.05$.

The effect of map dimensionality on WRF response error shown indicated that errors were reduced when the pilot flew with the two-dimensional map, $F(1,108)=6.364$, $p<.05$. There was no significant main effect of frame of reference on WRF response error. Figure 8 shows that direction of travel significantly influenced WRF response error, $F(1,108)=5.852$, $p<.05$. Errors were reduced when the pilot was heading in a

northerly direction. Figure 8 also depicts a marginally significant interaction between direction of travel and map frame of reference on WRF response error, $F(1,108)=5.852$, $p=.055$. The interaction seems to have been a result of dramatic increases in WRF response errors when the direction of travel on the fixed map was in a southerly direction rather than a northerly direction.

DISCUSSION

The purpose of this study was to examine and compare a more radical design of instrument approach plates with a more traditional representation. Recall that the currently proposed electronic plate design procedures attempted to improve traditional top-down planar approach plates (Kuchar et al., 1993; Multer et al., 1993; Hansman et al., 1992) or to improve the conditions in which they were used (O'Hare et al., 1990) rather than implement revolutionary design procedures. The current study compared a two-dimensional with three-dimensional maps and fixed versus rotating frames of reference to determine which designs of future approach plate displays would best support flight, navigating an aircraft to touchdown, while also supporting situation awareness. Additionally, direction of travel was examined to determine whether or not problems with left-right incongruencies occurred while using the fixed displays on southerly headings.

Flight Path Performance

Map Dimensionality. Flight control was enhanced with the two-dimensional display, allowing subjects better control of the aircraft along the vertical and lateral axes with the two separate planar displays than with the single three-dimensional representation. The results of this study appear to contradict those of previous studies (Wilkens &

Schattenman, 1968; Grunwald et al., 1981; Haskell & Wickens, 1993), which found that three-dimensional displays supported superior flight control performance. In interpreting the reasons for this contradiction, it is important to note that subjects reported having difficulty with the flight controls while using the three-dimensional display. Furthermore, flight path tracking became increasingly difficult as the aircraft flew further away, perceptually, from the subject. Additionally, some subject feedback seemed to point to problems due to ambiguities along the viewing axis, similar to those noted by Andre, et al. (1990) as their subjects flew closer to navigation waypoints. In this regard it is important to note that the current study had an important feature of similarity with Andre et al. (1990) that was not characteristic of the other studies described above. That is, both this study and that of Andre et al. presented a distant "wide view" perspective as subjects were required to fly to specific waypoints in a volume of space. In contrast the studies that have reported a superiority of three-dimensional displays provided a close-in view, with a viewpoint positioned directly from the aircraft's perspective, and a line of sight along the flight path. This latter perspective appears to suffer less from the ambiguity problem since there are not precise points to reach that are off of the viewing axis.

While ambiguity is inherent in three-dimensional displays, Wickens (1992) has used the proximity compatibility principle (PCP) as a framework for arguing that three-dimensional object displays should support integration tasks while two-dimensional displays should support focused attention tasks. Since flight control is an integration task requiring information integration across three dimensions of space, performance should have been supported better with the three-dimensional display, yet this was not the case. Two reasons may be offered.

First, the flight task as implemented here, with simplified flight dynamics and absence of predictor symbols, lessened the need for integration. In particular, Haskell and Wickens (1993) pointed out the importance, in their three-dimensional display, of the integration of lateral and vertical current information with lateral and vertical predicted information that the display provided. Furthermore, normal cross coupling between roll and pitch in the flight dynamics were not used in the present scenario. As these features were absent here, the task may well have been one in which sequential control of lateral and vertical axes was employed on both two- and three- dimensional displays. As Haskell and Wickens (1993) study revealed, sequentially controlled axes are better supported by separate displays.

Second, it is evident that three-dimensional displays will have potential costs, across both focused and integration tasks, related to resolution and ambiguity along the line of sight; hence, there are costs that are irrelevant to the PCP. These costs were observed by Andre et al. (1990) and clearly impose a degrading influence here.

Frame of Reference. Traditionally, approach plates are printed and viewed in a north-up fashion (from a WRF). There is, furthermore, a strong argument for north-up approach charts in electronic form because of the complexity in text positioning imposed when the electronic map rotates. Still, these arguments have not impeded the development of possible alternatives to display or map design. Several studies have investigated the frame of reference issue in regards to flight control (Wickens et al., 1989; Aretz, 1991; Harwood et al., 1991; Barfield et al., 1992). In each study, whether the display reference frame was defined as inside-out, track-up, or pilot's eye, the ERF display supported superior flight control. The results from this current study were consistent with those conclusions, indicating that the rotating track-up (ERF) display was better for lateral flight control no matter whether the two- or three-dimensional prototype was used. Superior performance was expected for lateral flight control using the ERF display due to the congruencies between left-right

on the map and left-right control inputs. The ERF display essentially simplified the flight controls.

The significant advantage of the ERF frame of reference on lateral flight control was not present for vertical flight control. Vertical control is not reversed in compatibility by changes in frame of reference, so it is not surprising that one would not find an effect of frame of reference on vertical control.

The two-way interaction between map dimensionality and frame of reference on vertical RMS, observed during both straight and turn segments, indicate that the two-dimensional maps follow the trend supported by theory and data from previous studies. In these studies, the rotating map was found to be better for flight path performance, yet the three-dimensional display supports the opposite performance. This interaction appears to be the result of the poor performance in the three-dimensional rotating map condition. It was during this condition that the sky track masked/overlapped the ground track because the viewpoint of the display was directly behind the aircraft. This perspective would thereby eliminate the subjects' ability to judge the aircraft's altitude unless they were off track laterally.

<u>Direction of Travel.</u> It is important to keep the left-right control of the aircraft congruent with the left-right

depictions on the map for navigation and flight control. Otherwise mental rotation is required in a manner that imposes performance costs (Aretz, 1991; Aretz & Wickens, 1992). This congruency is sustained when the pilot is flying in a northerly direction using a fixed north-up map or flying in any direction using a rotating map. Direction of travel was examined in the current study to determine if there were pilot difficulties with left-right incongruencies. The data from this study indicated that direction of travel significantly influenced lateral RMS while having no effect on vertical RMS. Lateral flight control was superior while traveling in a northerly direction; this was expected as long as left-right congruencies existed between the flight controls and the map. The absence of a difference between north and south on vertical flight control is also not surprising. Direction of travel which is defined by movements within the planar axes should not have any significant effect on movements in the vertical axis.

However, it was somewhat surprising that direction of travel did not influence the north-up map more than the track-up map as Harwood and Wickens (1991) and Aretz (1991) had observed (i.e., an interaction between map frame of reference and direction of travel was not obtained). This additivity suggested that the cost of mental rotation may

not have been responsible for the general performance decrement that was observed with the north-up map. An alternative explanation is that once some degree of mental rotation was required (with the north-up map), its costs were nearly as great for the smaller rotations required on north bound legs as for the larger ones required on the south bound ones. Some direct evidence for mental rotation, supported by the critical interaction between frame of reference and direction of travel, is provided in the situation awareness tasks to be described next.

Situation Awareness

The three judgment tasks were used to assess situation awareness in the different display conditions. Pilots must be able to make judgments concerning hazards, threats, and potential conflicts while performing particularly challenging aviation tasks. As Kuchar and Hansman (1993) point out, pilots may remain overly dependent on ATC terrain avoidance clearances without taking the responsibility for checking their own information in this regard. Recall that this may have been an attributing factor in the 1973 Dulles Crash (O'Hare & Roscoe, 1991). The pilots possess the necessary information to make their own judgments, yet it is not easily retrieved. Therefore, future designs must take into consideration the enhancement of situation awareness.

Map Dimensionality. Theory suggests that three-dimensional displays should support situation awareness better than two-dimensional displays because they are more "natural" or "compatible" representations of the pilot's view out the windscreen (Wickens, 1990; O'Hare & Roscoe, 1991). The results of this study indicated that there were no significant effects of map dimensionality on the time required to respond to questions regarding the lateral and vertical information about critical (i.e., closest) terrain features; however, the three-dimensional map did significantly increase response error of all three judgments: relative bearing (ERF), height, and absolute bearing (WRF) of the nearest terrain feature.

The findings of the current study, that three-dimensional displays do not support the location of objects in three-dimensional space, contradict those of Bemis, Leeds, and Winer (1988) and Ellis, McGreevy, and Hitchcock (1987), who found that three-dimensional displays supported significantly superior performance for threat detection and hazard identification respectively. Our findings showed superior performance of the two-dimensional display on the response error measures.

The difference in performance between the two display formats seems to come from the nature of the judgment tasks themselves. Again, recall that the PCP suggests that

"dimensionally integrated" displays, such as the three-dimensional display, should support better performance on integration tasks while this advantage is eliminated when focused attention is required along a single axis. It was, in fact the case that the judgment tasks in this experiment were not integrative in nature, requiring sequential judgments along the two orthogonal axes, rather than simultaneous integration of both. This would account for better performance using the two-dimensional display which presented these two axes explicitly and linearly for focused attention tasks. This argument is supported by the data of Tham and Wickens (1993), who found that the two-dimensional display better supported judgment tasks along a single axis.

In contrast to procedure employed in the current study, Bemis et al. (1987), and McGreevy et al. (1988) implemented integration tasks to the exclusion of focused attention tasks. Their findings suggested that three-dimensional displays supported judgment performance better than two-dimensional displays.

Frame of Reference. It is reasonable to assume that the responses to either the relative or absolute bearing questions would require some form of mental transformations (i.e., mental rotation). In particular, either an ego referenced question with a north-up display or a world referenced question (absolute bearing) in a rotating display

should impose mental rotation requirements while flying south.

Data indicated a marginally significant effect of frame of reference on ERF response latency, indicating superior performance with the rotating map. This result was expected when considering the cognitive operation of mental rotation, which is required with the alignment of WRF with the ERF (Aretz, 1991). Subjects presumably were required to use a mental rotation strategy in the fixed map condition to make the necessary alignments before responding, thereby increasing response latency. The rotating map eliminated the need for this cognitive transformation. Again, however, as with the effect of frame of reference on lateral error, it was somewhat surprising that the fixed map cost for ERF judgments was not enhanced during the south bound flight legs.

There was no difference between two frames of reference for WRF response latency. One may have expected the fixed map to be quicker for WRF responses for the same reason that the rotating map was quicker for ERF responses. Studies have shown that the location of objects in the world is better supported by the WRF display (Aretz, 1991; Harwood & Wickens, 1991).

Direction of Travel. While the data indicated no significant effect of direction of travel on either ERF or

WRF response latency, main effects were found for height error and absolute heading error. The effect of direction of travel on vertical judgment, shown in Figure 7, may be due to differences in the subjects' ability to discriminate altitude differences between the aircraft and the terrain features along the line of sight. In most circumstances as the subject was flying north, the terrain was perceived to be closer. Since a perspective three-dimensional rendering was used, it was easier to discriminate altitude differences when the aircraft and terrain appeared to be closer than when they were perceived to be further away, as was the case during the south bound legs. Although height judgments should be independent of direction of flight, the previous explanation would account for the interaction between frame of reference and direction of travel, which indicates a greater cost of south bound flight in the rotating map condition.

The influence direction of travel on WRF error indicated that subjects generally performed better when flying in a northerly direction than when flying south, independent of whether the map was rotating or fixed. This effect may have been a result of two separate mental rotation strategies required during south bound legs. These strategies are addressed below. The interaction between direction of travel and frame of reference was surprising.

It was expected that WRF judgment performance with the fixed map would be relatively independent of direction of travel. However, Figure 8 shows that it is the error for the rotating display that remains relatively constant over northerly and southerly directions of flight while it is the fixed map performance that is greatly degraded when the direction of travel is in a southerly direction. These results may be accounted for in two ways. First, the sequence of judgment responses necessitated two mental rotation strategies. Recall that the subjects made the ego referenced judgment before the world reference judgment. In the fixed map condition when flying south, subjects may have use a mental rotation strategy to align their heading on the map with that of the 12 o'clock position on a clock in order to give the ERF judgment regarding the nearest terrain hazard. However, this first mental rotation may have made it necessary for the subject to mentally rerotate the map back to its original position for the WRF response, a second mental transformation that may have enhanced the possibility of error.

A second possible explanation is that subjects simply performed extremely well with WRF judgments in the fixed map condition while heading north. This synergistic relationship may have resulted from the canonical (i.e., north-up) orientation of the map while flying in a northerly

direction. The remaining three points on the graph in Figure 8 appear to be similar. The single point displaced downward (lower error) because of this "synergism" would effectively produce the observed interaction.

3D Design Implementation: Where Do We Go From Here?

Just as the pilot, confronting a map, must ask the question, "Where do I go from here?", so a researcher, confronting data from a first research investigation in an area, will ask the same question.

Although this study points to the benefits of rotating two-dimensional displays (i.e., those with an ERF view), three-dimensional display design should not be abandoned since several studies have identified their significant benefits. Furthermore, the three-dimensional display used in the current study was probably not optimally designed for the required tasks. There were a host of choices that we needed to make in finalizing the actual three-dimensional implementations used here, and some of these choices needed to be made without supporting performance data.

There are a number of issues that need to be examined in the design of three-dimensional displays. For instance, frame of reference requires further investigation. With the inclusion of an ERF view in three-dimensional design, viewing distance becomes another parameter to consider. This experiment used a "track" view, in which the view point

was always at the edge of the map, rather than a "tether" view, in which the viewpoint followed behind the aircraft. The track view, therefore, created problems in the current display by imposing difficult flight control, at far distances when the display resolution was low. This shortcoming would be addressed with a tether view. While there may be some merit in sustaining a constant distance behind the aircraft as presented by the tether view, thereby enhancing the judgment of error, other problems may arise because the entire simulated world would not be in full view at all times.

Field of view and viewing elevation angle are both important parameters in the design of three-dimensional displays. Recent investigations of field of view (e.g., Barfield et al., 1992; Wickens, 1992) have proposed scene magnification for navigation tasks. Since the design of approach plates must support both flight control and situation awareness, there must be an optimal field of view to support both tasks providing knowledge of features and landmarks, as is typical of current approach plates.

The viewing angle in the current study was 29 degrees. Recent studies would argue that an appropriate elevation angle is between 30-45 degrees (Eley, 1988; Kim et al., 1987). Barfield and his colleagues would argue that the higher end of this range is better than the low end. Data

collected by Yeh and Silverstein (1992) indicate a trade-off, such that vertical judgments are better supported by the lower elevation angles and horizontal judgments are better supported by the higher angles. Again, the effect of this parameter should be further investigated to find the optimal viewing angle for the three-dimensional display.

Finally, future work should address three limitations in this current, first study of three-dimensional approach plates. First, our situation awareness tests did not fully assess three-dimensional integrated terrain awareness. Second, flight control itself was difficult in both display types because of the absence of predictors. Third, as was noted in the results, there were problems with altitude judgments on the rotating three-dimensional map because the view was from directly behind the aircraft. Follow-on studies will address these issues in regards to displays for terminal area navigation.

In summary, the two separate display panels in the two-dimensional display were superior to the three-dimensional display in regards to the dependent measures of flight control and judgment tasks. Furthermore, the rotating ERF view supported flight control performance better than the fixed WRF view while there was relatively no difference for measures of situation awareness. It is apparent that

acceptance of three-dimensional displays for approach plates is dependent on further investigation in this domain.

FIGURES

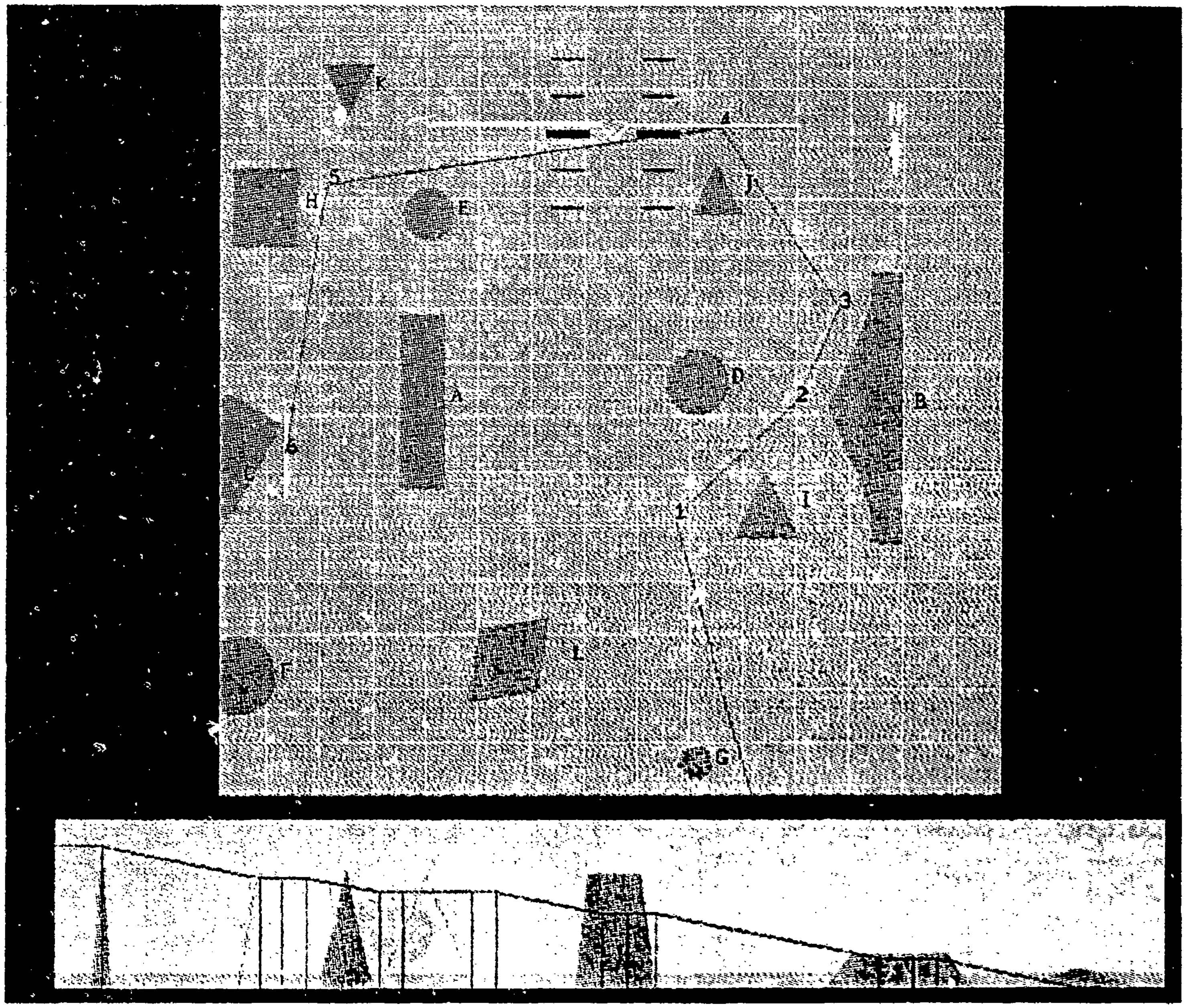

Figure 1. Separate panels in the two-dimensional display as seen by the subjects.

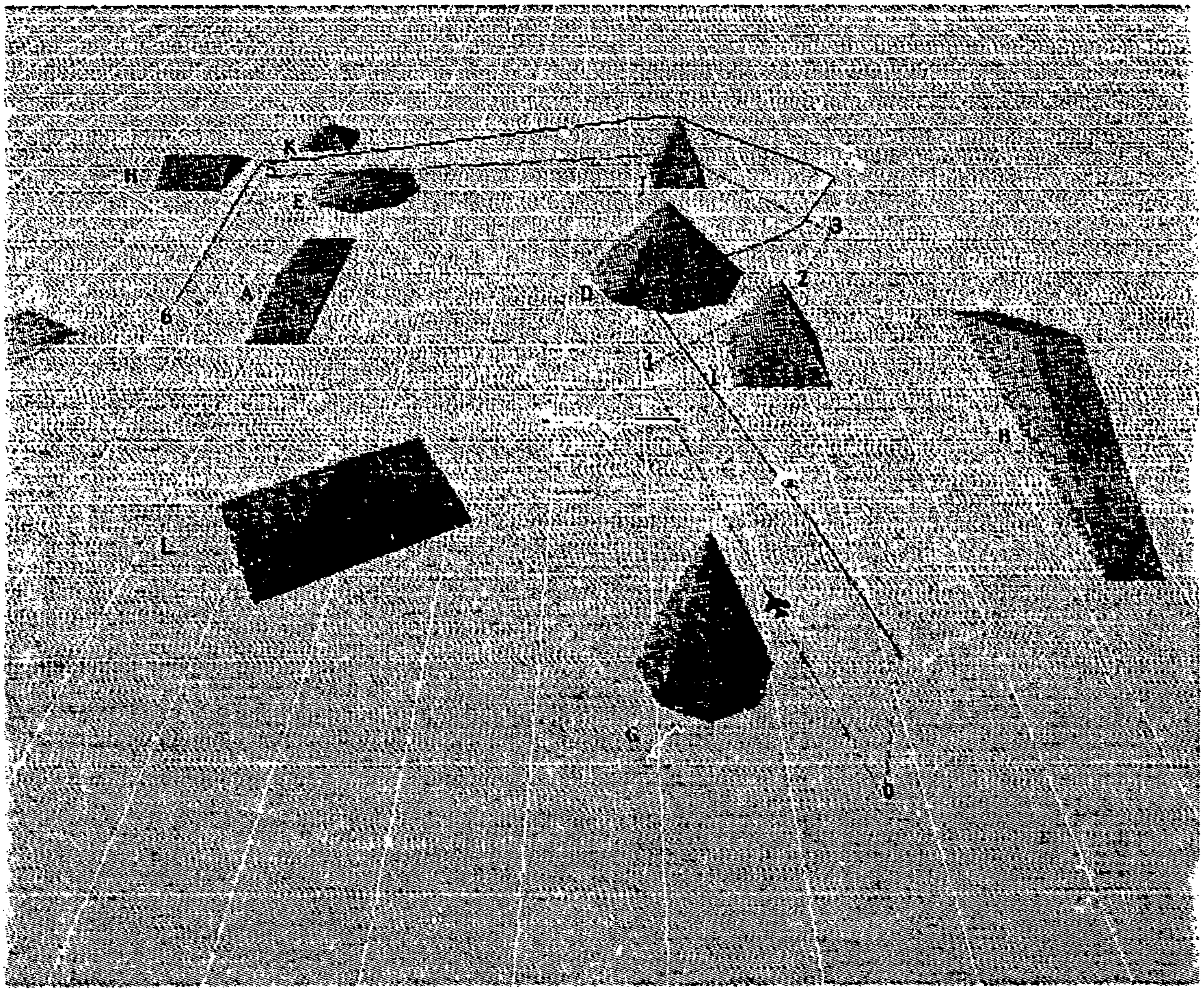

Figure 2. Three-dimensional display as seen by the subjects.

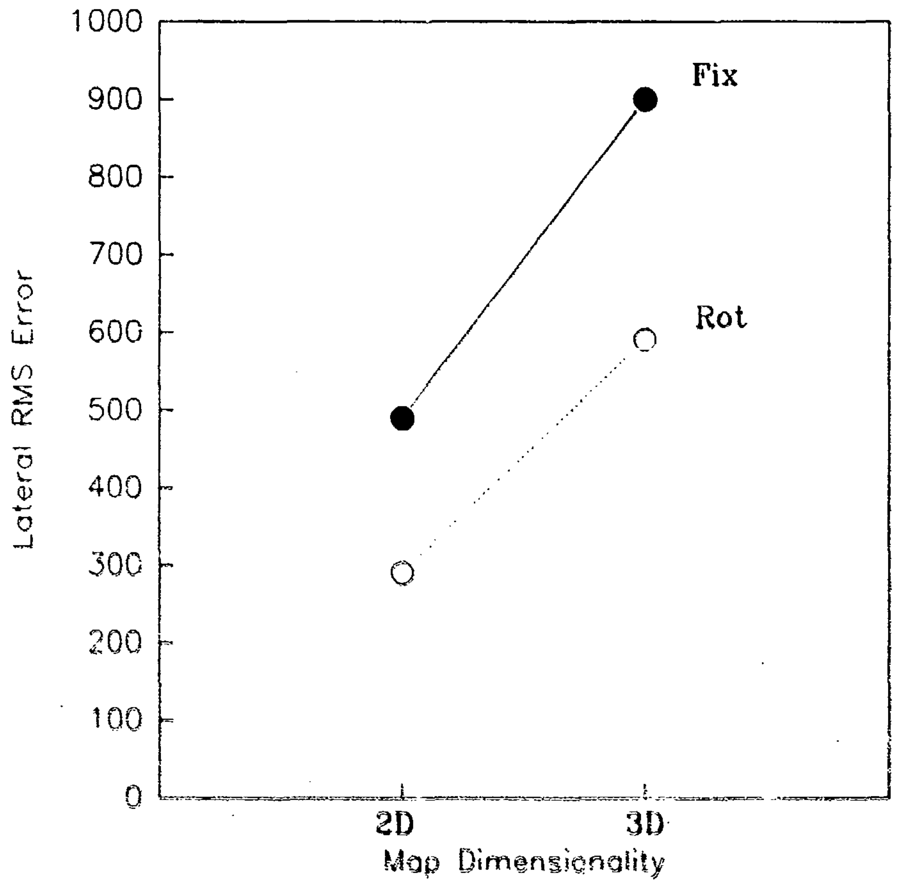

Figure 3. Lateral RMS error as a function of map frame of reference and map dimensionality.

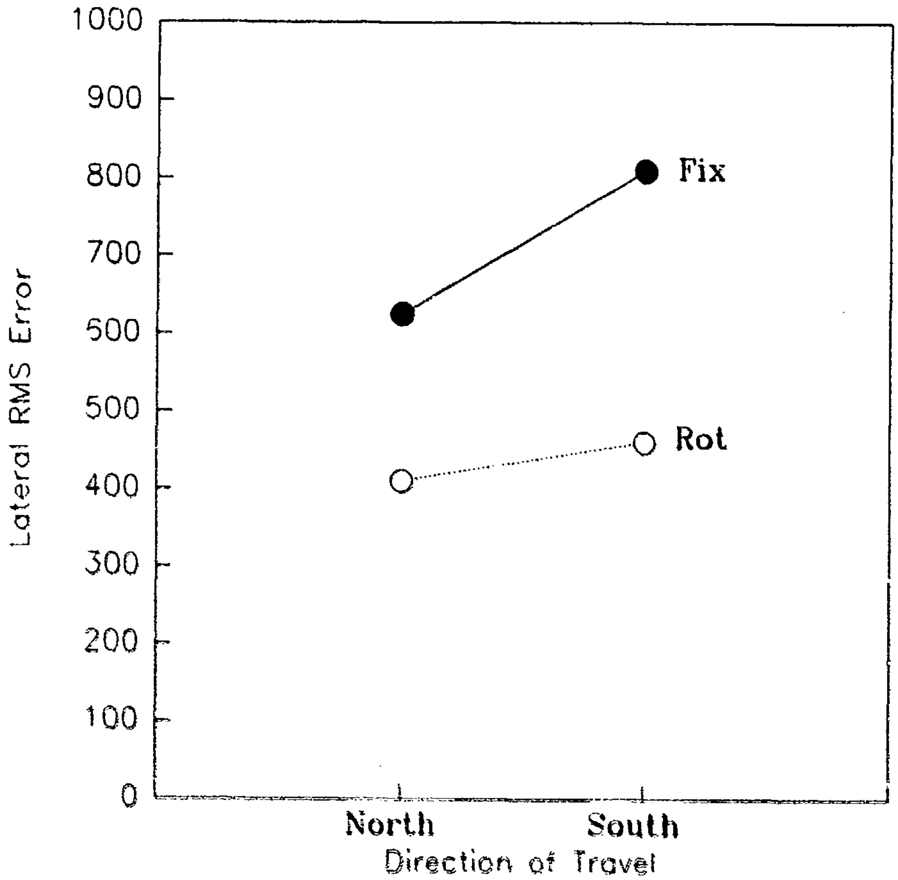

Figure 4. Lateral RMS error as a function of map frame of reference and direction of travel.

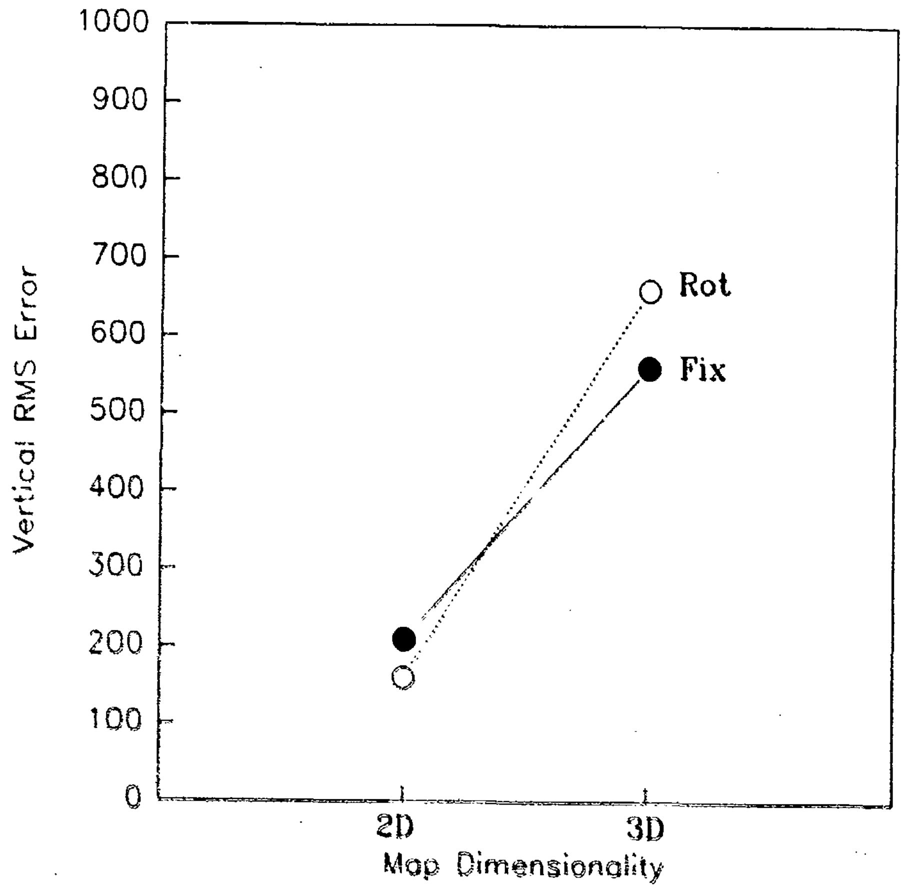

Figure 5. Vertical RMS error as a function of map frame of reference and map dimensionality.

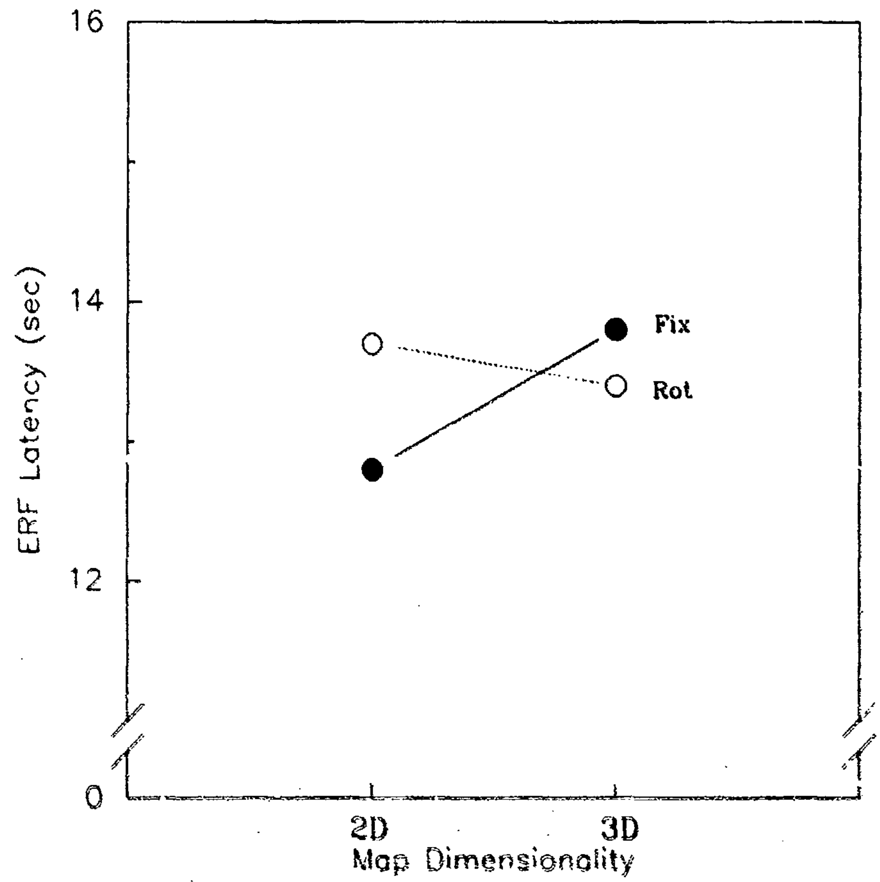

Figure 6. ERF response latency as a function of map frame of reference and map dimensionality.

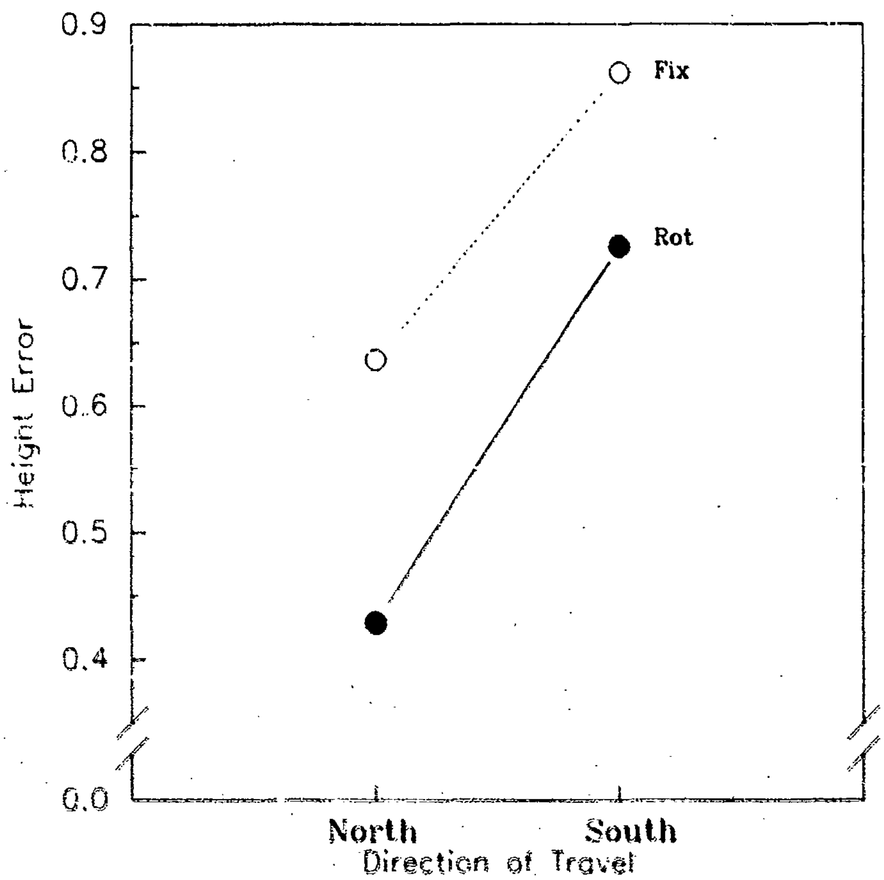

Figure 7. Terrain height error as a function of map frame of reference and direction of travel.

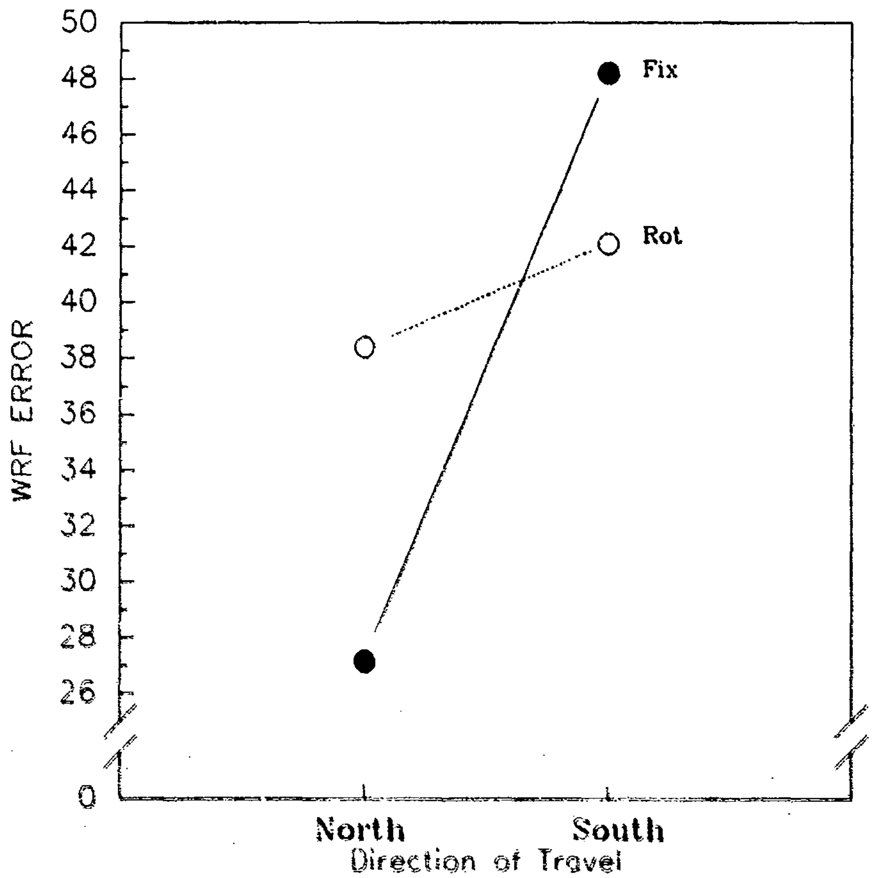

Figure 8. WRF response error as a function of map frame of reference and direction of travel.

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